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ARTICLE

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DIETARY SMALL MILLETS PROMOTE GUT HEALTH

SREERAMA KRUPANIDHI*

The longevity of herbivorous animals is comparatively longer than the carnivorous organisms, primarily because there is a remarkable difference in their gut microbes and gut length. Persistently, the herbivorous organisms rely on the foliage of plants as their fodder that is enriched with fiber which upon hydrolyzing in intestinal milieu yields short chain fatty acids that intangibly impart good health.

A few microbes reported in human intestine are Prevotella, Faecalibacterium, Roseburia, Ruminocococcus, Blautia and Eubacterium. They produce short chain fatty acids such as butyrates, acetates and propionates by fermenting the dietary fiber. These by-products contribute for intestinal mucosal health, gut barrier integrity, gut immunity, systemic immunity, metabolic regulation, anti-obesity, anti-atherogenic etc. As a result, there is widespread use of pre-biotics and pro-biotics supplementary capsules.

Therefore, the dietary small millets (Foxtail, Little, Kodo, Brown Top, Barnyard), being less moderately consumed in India due to lack of awareness particularly among the urban population, are rich in fiber and mineral nutrients that support the growth of gut microbiota, mucosal immunity and systemic health.

Introduction

The World Health Organization (1948) defined health as "a state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity." This definition marked a significant shift toward a holistic view of human well-being.

Over time, a range of global challenges - including environmental pollution stemming from the industrial revolution and warfare, the emergence of communicable diseases and viral pandemics, the rise of lifestyle-related illnesses, corporate-driven stress, food and fodder scarcity, contaminated drinking water, and energy shortages - have underscored the interconnectedness of human, animal, and environmental health. In response, the concept of "One Health" has gained prominence in the year 2022. Supported by the Quadripartite alliance - comprising the Food and Agriculture Organization (FAO), World Health Organization (WHO), World Organization for Animal Health (WOAH), and the United Nations Environment Program (UNEP) - the One Health approach promotes an integrated and unifying framework. Its goal is to optimize the health of people, animals, and ecosystems, recognizing their deep interdependence and the need for collaborative, cross-sectoral strategies to tackle global health threats.

The National Food Security Act (NFSA), 2013, was enacted by the Indian Parliament to ensure food and nutritional security by providing subsidized food grains to the economically vulnerable sections of society. As part of this initiative, the Indian government also emphasized the promotion of Nutri-cereals, especially millets, by encouraging their cultivation, processing, and consumption. This move aims to enhance dietary diversity, improve nutritional outcomes, and support climate-resilient farming practices.

* Former Dean & Professor of Biosciences, SSSIHL, Prasanthinilayam, and Former Dean & Professor of Biotechnology, VFSTRU, Vadlamudi, A P India.
Residence: Vijaya Sai Residency, Chenchupeta, Tenali 522202 A P India
e-mail: sknbirac@gmail.com

Considering the nutritional and health benefits of millets, the UNO and the Government of India have given them prominence and declared the year 2023 as the "Year of Millets". Dr. Khadar Vali, the Millet Man of India, was honored with the Padma Shri, a prestigious fourth-highest civilian award given by the President of India in 2023. Thus, interest in millet-based foods is being rejuvenated and is reviving public attention, leading to the popular phrase about millets: "The Forgotten Nutritional Powerhouses". Due to their versatile health benefits compared to other cereals, millets are treated not only as nutraceuticals but also more aptly as "healing grains" (Dr. Khadar Vali, Popular Talk). As shown in Table 1, the nutritional value of millets is not only comparable to other cereals but also found superior, as they are endowed with a high proportion of fiber, minerals, and iron content[1,2].

In the present attempt, an emphasis is placed on examining the impact of dietary small millets, which act as prebiotics, on the growth and survival of gut microbiota (probiotics). The metabolic byproducts produced by these microbes, known as postbiotics, are further evaluated for their influence on gut and systemic health in both ruminant and non-ruminant mammals.

Dietary Small Millets

Millets, rice, and wheat are all classified as cereals. However, while rice and wheat dominate urban diets, millets, despite their health benefits, are often overlooked. A fundamental distinction lies in their photosynthetic pathways: millets are C4 plants, meaning they fix carbon dioxide through a two-step process, first in the mesophyll cells, then in the bundle sheath cells, which allows them to thrive in dry and arid environments. In contrast, rice and wheat are C3 plants, fixing carbon dioxide in a single step and requires abundant water for cultivation.

Among the dietary small millets, brown top millet, barnyard millet, foxtail millet, Kodo millet, and little millet were widely cultivated and consumed in ancient India[1,3]. Today, their use continues, however, largely limited to certain rural communities. They are gluten-free, an additional attribute of millets to opt for as a bulk dietary component. The decline in millet consumption must have been tied to industrialization, commercialization, and changing urban lifestyle patterns, which favor convenience over traditional dietary wisdom. This shift has contributed to a rise in lifestyle-related health issues in urban populations.

Millets, like other cereals, provide a substantial amount of carbohydrates, meeting essential physiological needs. However, where they truly excel is in their fiber content, which is significantly higher than that of rice and wheat. This makes a crucial difference nutritionally. Millets contain both soluble and insoluble dietary fiber:

- Soluble fiber forms a viscous gel-like substance in the gut that traps sugars, cholesterol and fats, reducing their instant absorption into the bloodstream.
- Insoluble fiber adds bulk to the stool, promoting smooth bowel movements through the colon and rectum.

Table 1 presents a comparative analysis of the composition of millets, rice, and wheat. Nutritional values indicate that millets not only provide adequate carbohydrates and essential minerals, but also offer high dietary fiber, essential for gut health.

In contrast, the low fiber and high carbohydrate content of rice and wheat (Table 1) do little to support the growth of beneficial gut bacteria. A deficiency in such gut

Table 1. The values* of nutritional ingredients in 100 g dry cereals**

Cereals	Protein	Carbo Hydrate	Fat	Minerals	Fiber	Calcium	Phosphorous	Iron	Energy	Thiamine	Niacin
Brown Top	13.6	71.0	6.5	-	9.0	28	293	17.7	422	0.60	4.6
Foxtail	12.3	60.2	4.3	4.0	6.7	31	290	2.8	351	0.59	3.2
Little	7.7	67.0	4.7	1.7	7.6	17	220	9.3	329	0.30	3.2
Kodo	8.3	65.9	1.4	2.6	5.2	35	188	1.7	353	0.15	2.0
Barnyard	6.2	65.5	4.8	3.7	13.6	22	280	18.6	300	0.33	4.2
Rice	6.8	78.2	0.5	0.6	1.0	33	160	1.8	362	0.41	4.3
Wheat	11.8	71.2	1.5	1.5	2.0	30	306	3.5	348	0.41	5.1

*Nutritional values vary slightly depending on the source of cultivation.

** The nutritional values of a few cereals are compiled from the 'Dietary guidelines for Indians' released for the purpose of public use by the National Institute of Nutrition, Hyderabad, India.

microbiota is increasingly recognized as a contributor to systemic health issues, a topic explored in detail in the later section of this review.

The nutritional values of millet, as shown in Table 1, indicate that it contains significantly more dietary fiber than rice and wheat. This higher fiber content supports the growth and activity of beneficial gut bacteria, which utilize fiber as a primary energy source. The fermentation of soluble fiber by these microbes produces short-chain fatty acids (SCFAs) that offer substantial health benefits to both ruminant and non-ruminant mammals[1-4]. This possibly be one of the contributing factors to the greater longevity observed in ruminant mammals compared to their carnivorous counterparts.

In addition, the macronutrient composition - namely protein, carbohydrates, and fats - varies proportionally among millet, rice, and wheat (Table 1). While these macronutrients primarily support energy production and body mass development, they have limited impact on gut microbiota or gut health.

Furthermore, millet contains a higher proportion of iron, as indicated in Table 1. This iron exists in a bioavailable form, making it easier for the human body to assimilate and thereby beneficial for individuals suffering from various types of anemia.

Therefore, incorporating small millets as a major dietary component offers considerable health advantages and supports overall well-being (Fig. 1).

Gut symbiotic microbes

The inferior region of the gut components, namely the small and large intestines of humans, harbor predominantly beneficial microorganisms. These include bacteria, viruses, fungi, and protozoa - collectively numbering over 100 trillion. Interestingly, a greater number of bacterial cells are present in the gut than the total number of cells in the human body. Remarkably, the collective genome of these microbes far exceeds that of the human genome, which is approximately 3×10^9 base pairs. Over time, host-microbe interactions have evolved into a mutualistic relationship, where both host and microbes share resources and shelter. This partnership benefits both parties without causing harm.

Gut microbes have developed sophisticated molecular mechanisms to successfully colonize the nutrient-rich and supportive environment of the human gut[5]. In return, the host gains numerous benefits, including SCFAs, which are vital for gut health and systemic health[6-8]. The presence of the following beneficial bacteria is a strong indicator of a healthy gut, characterized by gut barrier integrity, stability, symbiotic interactions, intestinal mucosal health, gut-colon reflexes, gut immunity, and effective peristalsis for coordinated bowel movements [4,5,8,9].

A few good bacterial genera present in the gut are: *Prevotella*, *Faecalibacterium*, *Roseburia*, *Ruminococcus*, *Blautia*, *Eubacterium* and *Bifidobacteria*[10].

- *Prevotella*: It is present both in the oral cavity and gut primarily among ruminants. It exists in individuals who consume high-fiber diets.
- *Faecalibacterium*: It is present in abundance in the colon. It is a major producer of butyrates.
- *Roseburia*: It is found in the hindgut. It produces butyrate by digesting soluble fats and carbohydrates.
- *Ruminococcus*: It is a genus within Firmicutes. It is known to produce SCFAs using complex carbohydrates.
- *Blautia*: This genus is found in the hindgut. It is involved in a variety of metabolic processes and produces acetate.
- *Eubacterium*: A large and diverse genus. It is involved in carbohydrate fermentation.
- *Bifidobacteria*: This genus is associated with lactic acid production.

The enlisted prominent genera

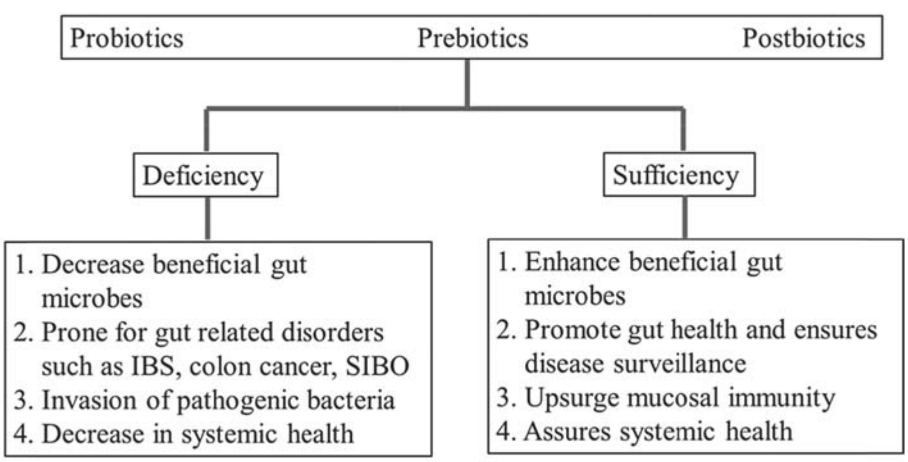


Fig. 1: The flow chart shows the influence of dietary small millets on the growth of beneficial gut microbiota and consequent systemic health. IBS: Irritable bowel syndrome; SIBO: Small intestinal bacterial overgrowth.

representing good bacteria (probiotics) in the gut exert influence through their products namely postbiotics (SCFAs) on the metabolism, anti-inflammation, resistance to colonization of invading pathogenic strains, energy source for colon cells, modulation of the immune system, gut barrier function and healthy status of an individual. Thus, the overall balance between healthy (beneficial) and unhealthy (pathogenic) microbiota within the gut is critical for maintaining systemic health and well-being of the host organism.

Short-Chain Fatty Acids (SCFAs)

Ruminant and non-ruminant mammals obtain SCFAs as byproducts of gut microbial fermentation. The major SCFAs: acetic (C2), propionic (C3), and butyric (C4) acids, are found in the gastrointestinal tract predominantly in their anion forms.

The term *short-chain fatty acid* is somewhat of a misnomer, as these molecules differ structurally and functionally from long-chain fatty acids such as palmitic acid or linoleic acid. Unlike typical fatty acids, SCFAs are highly water-soluble, lacking hydrophobicity generally associated with fats. Chemically, they are more accurately described as saturated, unbranched alkyl monocarboxylic acids containing 2 to 4 carbon atoms[11].

In mammals, SCFAs are primarily generated by gut bacteria in specific regions of the gastrointestinal (GI) tract:

- In ruminants, SCFAs are synthesized in the foregut (rumen) and hindgut.
- In non-ruminant mammals, they are predominantly produced in the large intestine.

The typical molar ratio of SCFAs produced through microbial fermentation is approximately:

- Acetic acid: 59%
- Propionic acid: 22%
- Butyric acid: 19%

Among these, butyric acid plays particularly a significant role in gut health, epithelial integrity, and cellular signaling, followed by propionic and acetic acid[12-16]:

- Butyric acid > Propionic acid > Acetic acid in terms of biological impact.

The primary substrate for SCFA production is dietary fiber, particularly non-starch polysaccharides (NSPs), which are abundant in plant-derived foods such as:

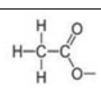
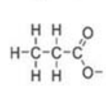
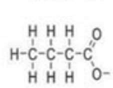
- Tubers
- Leafy and non-leafy vegetables
- Fruits
- Cereals
- Especially millets

In contrast, non-vegetarian food sources are devoid of dietary fiber and hence do not contribute to SCFA production.

Importantly, the digestive enzymes produced by the host GI tract, whether in ruminant or non-ruminant mammals, cannot hydrolyze dietary fiber. Therefore, mammals and lower groups of animals rely heavily on symbiotic gut microbiota to ferment dietary fiber and produce SCFAs, which are then absorbed and utilized by the host for various metabolic and immunological signaling processes.

SCFAs possess an aliphatic structure characterized by a carboxylic acid group (–COOH) attached to a saturated carbon atom (Table 2). Their pKa values indicate the extent of ionization in the mildly acidic environment of the colon (pH 5.4–6.5), enabling SCFAs to interact with proteins and receptors on the intestinal epithelium. This interaction facilitates their translocation across the colonic barrier into the gastro-hepatic circulation. Once in circulation, SCFAs act as signaling molecules by binding to G protein-coupled receptors (GPR41, GPR42, and GPR43), thereby triggering intracellular signaling cascades associated with the mitigation of several pathological conditions, including inflammatory bowel disease (IBD),

Table 2: Physical features of SCFA[17]

Microbial byproduct	Molecular structure	Chemical formula	Number of Carbon atoms	Molecular weight	pKa at 25ºC
Acetylide anion		$C_2H_3O–$	2	60.05	4.56
Propionate anion		$CH_3CH_2COO–$	3	74.08	4.67
n-butyric anion		$CH_3CH_2CH_2COO^-$	4	88.11	4.63

celiac disease, irritable bowel syndrome (IBS), colorectal cancer, obesity, and small intestinal bacterial overgrowth (SIBO)[14, 15, 18-21].

A reduction in SCFA production, often due to a loss of symbiotic gut microbes resulting from antibiotic overuse or insufficient dietary fiber, can impair epithelial cell proliferation and compromise tight junction integrity in the jejunum and colon. This disruption leads to increased intestinal permeability, commonly referred to as "leaky gut," promoting inflammation throughout the gastrointestinal tract. Consequently, existing evidence[18-21] strongly supports the health benefits of dietary fiber, particularly from millets, in promoting SCFA production and maintaining gut homeostasis.

Mucosal Immunity

Mucosal immunity is the first line of defense, spread along the length of the mucosal surfaces in the gut, respiratory tract, and urinary tract to protect against invading pathogens, antigens, etc. Interestingly, the mucosal surface is a large area that does not have a tough barrier-like skin and is therefore prone to pathogen invasion. The components that contribute to immunological defense in the gut include mucus, the gut epithelial cell lining, sIgA (secretory immunoglobulin A), antimicrobial peptides, immune cells such as dendritic cells, leukocytes and lymphocytes, and mucosa-associated lymphoid tissue (MALT)[22]. Peyer's patches in the gut and tonsils fall under MALT. The gut lining faces frequent challenges due to antibiotic medication, alcohol abuse, food of varying quality, and pathogens causing leaky guts, which may influence the elicitation of immune response, inflammation, or tolerance.

One of the immunoglobulin isotypes, namely sIgA, is a dimer predominant on the mucosal epithelial surface and serves to neutralize antigens. sIgA is composed of two IgA monomers that neutralize antigens, a J-peptide chain that joins the two monomers, and a secretory component that protects against degradation by intestinal enzymes. The sIgA–antigen immune complexes are expelled from the gut lumen through the ciliary movements of the gut epithelium.

In addition to the gut immune system, antimicrobial peptides (AMPs) in the gut[21,23,24] predominantly produced by beneficial bacteria and, to some extent, the gut epithelium, contribute to defense against harmful bacteria. They include:

- Defensins: These peptides, produced by Paneth cells, exert a broad spectrum of antimicrobial activity, protect the gut by killing harmful pathogens, disrupt their cell membranes, neutralize toxins, or interfere with bacterial cell wall synthesis. Defensins attract dendritic cells, T regulatory cells, and macrophages to the site of infection and promote cytokine production, thus contributing to gut homeostasis.
- Cathelicidins: These AMPs are produced in both the colon and small intestine in an inactive form and proteases activate them by partial proteolysis. They recognize and bind to pathogens adhered to the surface of the gut epithelium and participate in wound healing and gut tissue repair, thereby maintaining the integrity and health of the gut epithelium.
- Regenerating gene proteins: alpha/beta/gamma: These AMPs belong to the C-type lectin family and destroy Gram-positive bacteria by binding to their cell walls. They regulate gut epithelial inflammation and promote epithelial repair.
- Lysozyme: These enzymes, produced by Paneth cells in the gut lining, are antimicrobials that break down the peptidoglycan layer of bacterial cell walls, causing bacterial lysis. Thus, they help prevent gut infections and maintain gut health.

Cytokines are important signaling molecules not only in the lymphatic system but also in the gut lining, particularly play between mucosal epithelial lining and immune cells. They are involved in initiating and resolving inflammatory responses and responding to frequent threats in the dynamic gut environment. The following cytokines play key roles in inflammation, defense cell recruitment, tissue repair, and gut health: TNF-alpha, TGF-beta, IFN-gamma, IL-10, and IL-17[25, 26].

Dietary small millets, owing to their prebiotic properties and high fiber content, support the growth of beneficial gut microbes by serving as their nourishment. These microbes (probiotics), in turn, produce postbiotics, specifically short-chain fatty acids (SCFAs), which play a vital role in cellular signaling pathways. SCFAs facilitate the release of cytokines and activate immune cells, thereby contribute to the reduction of inflammation and promote gut tissue repair.

Health Due to Dietary Small Millets

Besides the presence of macronutrients, minerals, and fiber (Table 1), millets contain a reasonable quantity of antioxidants, such as polyphenols, flavonoids, and tocopherols. These antioxidants protect the host organism by neutralizing and scavenging free radicals - unstable molecules that, when overproduced, can damage cells and cause DNA breaks and cellular dysfunction. Cellular metabolism, including both catabolism and anabolism, generates large amounts of reactive oxygen species (ROS). Under healthy physiological conditions, these ROS are typically neutralized by enzymes and other molecules[27]. However, in diseased states, excessive ROS production leads to a condition known as oxidative stress. The antioxidants in dietary small millets help reduce oxidative stress and lower the risk of chronic diseases such as diabetes, obesity, cancer, cardiovascular disease, and chronic kidney disease[7,18-21].

In addition, the soluble fiber in dietary small millets absorbs water in the gut and forms a viscous gel. This viscous gel traps the digestive end products namely simple sugars, cholesterol and triglycerides and slows down their intestinal absorption which helps in remission from diabetes and cardiovascular diseases. The beneficial microbiota utilizes soluble fibers as their energy source, colonize in the gut and releases SCFAs as shown in the previous sections. These SCFAs involve in multiple health benefits through their participation in cell signaling and activation of immune cells. Millets promote the gut to be healthy by enriching beneficial bacteria, which can help alleviate various health issues. The prebiotic fiber in millets feeds these beneficial bacteria, leading to improved digestion, nutrient absorption, and even enhanced immune function. This gut-friendly effect of millets can contribute to the management of conditions like obesity, hormonal imbalance, diabetes, IBS, SIBO, colorectal cancer and high blood pressure[2, 28] (Fig. 2).

Recent case studies reported by the Asian Institute of Gastroenterology (AIG), Hyderabad, India, revealed that around 200 patients suffering from Inflammatory Bowel Disease (IBD) and Crohn's disease were successfully treated using Gut Microbiota Transplantation (GMT). The treatment, led by Dr. D. Nageswara Reddy and his team, resulted in complete remission, with patients no longer requiring medication.

These observations highlight the critical role of gut microbiota in managing chronic gastrointestinal disorders. In this context, small millets, due to their high dietary fiber content, serve as natural prebiotics - substances that feed beneficial gut bacteria. Therefore, regular consumption of small millets can help nurture a healthy gut microbiome, enhance digestion, nutrient absorption, and immune function, thereby contribute to overall systemic health.

***Preparation of Porridge Using Millets*:** To begin with, select the millet to be cooked. Measure out a quantity equivalent to two ounces by volume and place it in a bowl. This quantity of millet is sufficient for four people in the family for one day. After washing it two or three times, fill the bowl with ten ounces of water to allow the millets to soak. Cover it with a lid and set it aside for 6 to 8 hours, preferably overnight (Fig. 3a).

The next morning, transfer the contents of the bowl to a 3-liter pressure cooker and boil until two to three whistles are heard. Once the contents have cooled, scoop out the boiled millet and transfer it to another container (Fig. 3b), preferably a suitable earthen pot. Mix in approximately 14 ounces of buttermilk with a pinch of salt. Let the mixture is allowed at room temperature for 4 to 5 hours before consumption (Fig. 3c).

An interesting aspect of this porridge preparation is that 2 ounces of millets are mixed with 24 ounces of fluids (water used for boiling + buttermilk used for incubation), which invariably allows the fiber in the millet to become hydrated and contributes to support the nourishment of gut microbiota. The boiled millet and the enriched microbes in the prepared porridge offer significant health benefits, as discussed in earlier sections of this review.

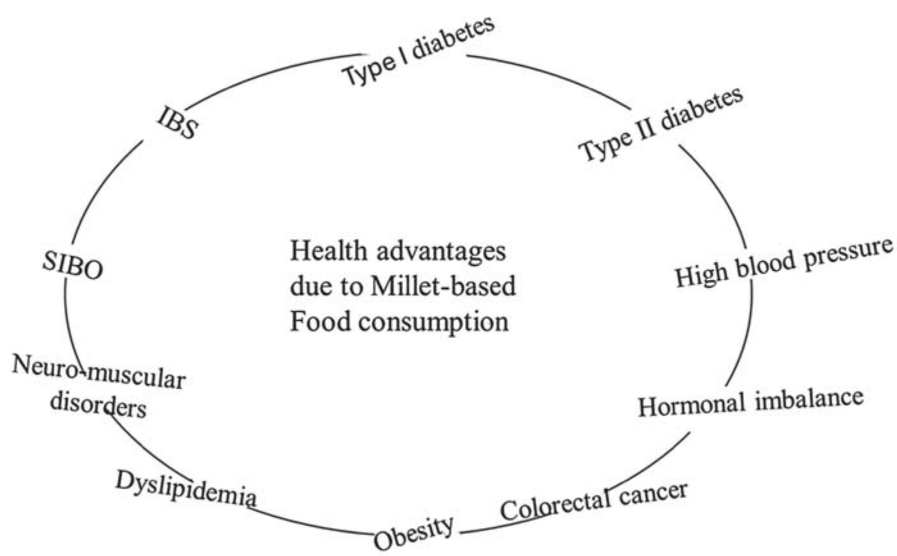


Fig. 2. The remission from the diseases shown is made possible due to millet-based food consumption. Abbreviations: IBS: Irritable Bowel Syndrome, SIBO: Small Intestinal Bacterial Overgrowth.

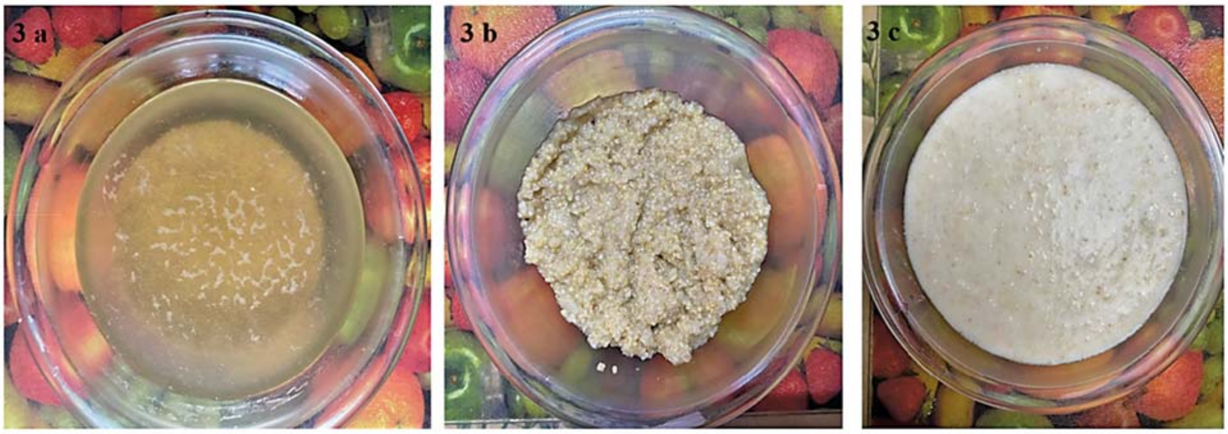


Fig. 3. Porridge preparation using millets: 3a: Millets soaked overnight for 8 hours, 3b: Boiled millets in a 3-liter pressure cooker; 3c: Boiled millets mixed with buttermilk kept aside for 5 hours before consumption.

Conclusion

Dietary small millets are nutrient-rich cereals, particularly notable for their high fiber content compared to other monocot grains. This fiber acts as a potential prebiotic, supporting the growth of beneficial gut microbiota. As a result, these microbes produce postbiotics - primarily short-chain fatty acids (SCFAs) - which can cross the intestinal epithelium, trigger downstream signaling pathways that activate immune cells and promote systemic health. Additionally, the antioxidant properties of small millets help mitigate oxidative stress and reduce the risk of DNA damage. Importantly, the beneficial gut microbes supported by such a diet are increasingly recognized as valuable in managing gastrointestinal disorders. Thus, incorporating small millets in our regular diet can contribute significantly to overall well-being and a healthier lifestyle. ❒

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